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Inhalation Transfer Factors for Air Pollution Health Risk Assessment

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ABSTRACT

To facilitate routine health risk assessments, we develop the concept of an inhalation transfer factor (ITF). The ITF is defined as the pollutant mass inhaled by an exposed individual per unit pollutant mass emitted from an air pollution source. A cumulative population inhalation transfer factor (PITF) is also defined to describe the total fraction of an emitted pollutant inhaled by all members of the exposed population. In this paper, ITFs and PITFs are calculated for outdoor releases from area, point, and line sources, indoor releases in single zone and multizone indoor environments, and releases within motor vehicles. Typical PITFs for an urban area from emissions outdoors are ~10^{-6}–10^{-3}. PITFs associated with emissions in buildings or in moving vehicles are typically much higher, ~10^{-3}–10^{-1}.

INTRODUCTION

Quantitative health risk assessments are routinely used to support environmental policy decisions. For toxic air pollutants, an evaluation of the human health risk caused by a pollutant release may be required as part of a permitting process.[1] Considerable attention has also been given to health risk evaluations for indoor pollution sources, such as environmental tobacco smoke.[2]

Health risk assessments that focus on the impact of a single source or source category involve several steps. For outdoor air releases, pollutant emissions are estimated, often as the product of an emission factor times the intensity of an activity. The emissions information is supplied along with meteorological data to a dispersion model to predict downwind concentrations. Some information about the downwind population is then provided to predict exposure and inhaled or absorbed dose. Finally, the health risk is estimated, often by multiplying the exposure or dose by a unit risk factor. For indoor air releases, a similar series of steps can be carried out. Emissions data can be combined with an indoor air quality model to predict indoor air concentrations. Then, concentrations can be combined with other information to evaluate exposure, dose, and risk.

For most primary pollutants, that is, those emitted directly from sources (rather than formed, for example, by chemical reactions in the atmosphere), concentrations, exposures, and doses are proportional to emissions. That is, if all other variables are fixed, then doubling the rate of emissions leads to a doubling of the inhalation dose rate. An example for which proportionality applies well is benzene, which is emitted from combustion sources (e.g., motor vehicles and cigarettes) and evaporation (gasoline and solvents). Benzene is not formed nor degraded to a substantial degree by atmospheric reactions on the residence time scale of air in an urban air basin or an indoor environment. Therefore, exposure to benzene emissions from a specific source scales linearly with the

IMPLICATIONS

A key step in assessing human health risk from air pollutant emissions is evaluating pollutant transport from the source to a receptor. This step usually involves the use of modeling techniques with substantial data requirements. In this paper, we introduce the concept of ITFs for describing source-to-receptor relationships. This concept is useful for comparing the magnitude of exposures to pollutant emissions released under different conditions. With the aid of these parameters, preliminary health risk assessments for air pollutant sources can be more easily conducted.

magnitude of the emissions. On the other hand, the proportional relationship between emissions and dose would not apply for O_3, a secondary pollutant whose concentration depends on emissions of precursor hydrocarbons and nitrogen oxides in a complex, nonlinear manner.

The linear relationship between emissions and dose for many pollutants suggests the idea of an inhalation transfer factor (ITF) to facilitate estimating health risk. We define the ITF to be the dimensionless ratio of pollutant mass inhaled to pollutant mass emitted. Multiplying an appropriate ITF by expected pollutant emissions would produce an estimate of inhaled dose. Armed with tables of ITF values for different releases and exposure scenarios, an estimate of health risk could be obtained as the product of three terms: amount of emissions (mass emitted) times ITF (mass inhaled per mass emitted) times unit risk factor (risk of adverse outcome per mass inhaled). Although the ITF does not capture all of the complexity of the relationship between emissions and dose, it can provide a useful preliminary estimate. Based on an evaluation using ITFs, an informed decision can be made about whether more detailed exposure modeling is necessary. For example, if an ITF-based estimate of risk is more than an order of magnitude below the level of regulatory concern, that might be judged sufficient evidence to deem the exposure acceptable. The ease of use of ITF may also facilitate comparing exposure scenarios, thereby assisting policymakers in prioritizing efforts to reduce environmental risk.

In some cases, the exposure or dose received by a single person, such as the maximally exposed individual, is the primary concern in a health risk assessment. In other cases, the total population dose is of interest. For these cases, we define the population inhalation transfer factor (PITF). The PITF is the dimensionless ratio of pollutant mass inhaled by all exposed members of a population to the mass emitted.

The ITF and PITF are closely related to the idea of exposure effectiveness, which was defined by Smith to be "the fraction of released material that actually enters someone's breathing zone."[3] Thompson and Evans have used a similar construct in a population exposure assessment for perchloroethylene from dry cleaners.[4]

Our use of the phrase "pollutant mass inhaled" corresponds to what Zartarian et al. call the inhalation dose, or, more generally, intake dose.[5] The inhalation dose rate is the product of the breathing rate (m^3/hr) times the species concentration in the breathing zone (e.g., μg/m^3). In assessing inhalation transfer factors (ITF or PITF), we consider both transient and steady emissions. For the transient case, we compute transfer factors as the ratio of the inhalation dose to the mass emitted. For steady emissions, we compute transfer factors as the ratio of the inhalation dose rate to the mass emission rate.

In this paper, we demonstrate methods of calculating ITFs. We develop examples for sources emitted outdoors, inside a building, and inside a vehicle. The results add insight into the relative importance for human exposure of pollutant releases under different conditions.

METHODS

Inhalation Transfer Factor

The ITF quantifies the fraction of a pollutant emitted into air that would be inhaled by an individual in a specific location for a given release and transport scenario. For an episodic pollutant release, the ITF is defined as

$$\mathrm{ITF} = \frac{\text{mass inhaled}}{\text{mass emitted}} = \frac{\int C(t) Q_B(t)\,dt}{\int E(t)\,dt} \tag{1}$$

where $C(t)$ is the incremental breathing-zone concentration of the pollutant caused solely by the emission source (g/m^3), $Q_B(t)$ is the breathing rate (m^3/hr), and $E(t)$ is the emission rate of the pollutant from the source (g/hr). For a release of short duration, the integrals would be evaluated for a sufficiently long time, t, to encompass the entire event. For steady conditions (i.e., emission rate, meteorological conditions, and breathing rate), the ITF at a specific location would be estimated as the ratio of the integrands

$$\mathrm{ITF} = \frac{\text{mass inhalation rate}}{\text{mass emission rate}} = \frac{C Q_B}{E} \tag{2}$$

In addition to the individual ITF, we define a cumulative PITF as the fraction of the emitted pollutant that is inhaled by the entire exposed population

$$\mathrm{PITF} = \sum_{i=1}^{N} \mathrm{ITF}_i \tag{3}$$

where N is the number of persons exposed and ITF_i is the ITF for the ith individual in the population.

In an interior (building or motor vehicle) setting, eqs 4 and 5 give the PITF for short-term and steady releases, respectively.

$$\mathrm{PITF} = \frac{\sum_{i=1}^{N} \int C_i(t) Q_{Bi}(t)\,dt}{\int E(t)\,dt} \tag{4}$$

$$\mathrm{PITF} = \frac{\sum_{i=1}^{N} C_i Q_{Bi}}{E} \tag{5}$$

where the subscript i denotes a parameter value specific to the ith individual.

For an outdoor setting, the general expression for the PITF can be written as follows for an episodic release:

$$\text{PITF} = \frac{\iiint C(x,y,t)Q_B(t)P(x,y,t)dxdydt}{\int E(t)dt} \qquad (6)$$

where P is the density of the exposed population (persons per land area), x is the windward coordinate, and y is the crosswind coordinate.

For a steady outdoor release, the population ITF is estimated as

$$\text{PITF} = \frac{\iint C(x,y)Q_B P(x,y)dxdy}{E} \qquad (7)$$

Formally, the concentration C should be evaluated at the breathing height of the exposed individuals. For outdoor releases, the concentration at breathing height is well approximated by that at ground level, provided that the vertical extent of the plume is much greater than the breathing height, a condition that is generally satisfied. As presented here, any attenuation in indoor exposure to outdoor sources caused by pollutant losses in buildings is neglected. However, the methods could be extended to account for these. For indoor emissions, the well-mixed hypothesis is applied either for the building as a whole or for individual rooms in a building. Near-field effects associated with localized indoor sources, for example, use of a consumer product, are potentially important but not included here because adequate information is lacking.

The ITF at any location is independent of the quantity released, but does depend on geography, meteorology, and other site-specific features. In addition to these factors, the PITF is a function of the population distribution. Due to this variability, the same release from the same site would yield different ITFs and PITFs at different times. For screening purposes, it is possible to determine a reasonable range of ITFs and PITFs based on the range of conditions typically found at a site.

Outdoor Emission Sources

Outdoor emissions have been the focus of traditional air quality control programs. Sources are divided into stationary and mobile categories, with control measures varying for each type. For the present purposes, it is useful to divide sources into categories based on the spatial distribution characteristics of the release. In this paper, we will look at three outdoor release circumstances: (1) uniform source throughout a populated zone, (2) point source within a populated zone, and (3) line source within a populated zone. For the purpose of the examples in this paper, we will assume that the exposed population is uniformly distributed with density P over an area of finite extent. However, the PITF concept can be applied for any spatial distribution of population.

Well-Mixed Air Basins. When a source is diffuse, such as CO emissions from urban street traffic and winter smoke from wood-burning fireplaces, the pollutants within the basin can sometimes be adequately modeled by assuming that the basin is well mixed. For steady-state conditions,

$$C = \frac{E}{HWU}$$

and so eq 2 becomes

$$\text{ITF} = \frac{Q_B}{HWU} \qquad (8)$$

where H is the mixing height (m), W is the crosswind width of the well-mixed basin (m), and U is the wind speed (m/hr). Assuming a uniform population distribution throughout the basin, the PITF can be expressed as

$$\text{PITF} = \frac{PLQ_B}{HU} \qquad (9)$$

where L is the windward dimension of the air basin.

Elevated Point Source Emissions. For air pollutants emitted from a stationary point source, such as an exhaust stack from an incinerator or power plant, a Gaussian plume model may be used to estimate downwind pollutant concentrations. For steady release of a nonreactive contaminant, the time-averaged downwind concentration at ground level ($z = 0$) is estimated as[6]

$$C(x,y,H_E) = \frac{E}{\pi\sigma_y\sigma_z U}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\exp\left(-\frac{H_E^2}{2\sigma_z^2}\right) \qquad (10)$$

where σ_y and σ_z are the dispersion coefficients in the transverse and vertical directions, respectively. This expression assumes that dispersion occurs upward without bound. The effective height of the stack, H_E, takes into account plume rise because of buoyancy or discharge momentum. Empirically determined values of the dispersion coefficients as a function of downwind distance and atmospheric stability are based on the work of Pasquill[7] as modified by Gifford.[8] However, there are some limitations on using those curves, primarily due to the inadequacy of the experimental data.[9]

There have been several modifications to the Pasquill-Gifford (P-G) curves, that is, expressing the (characteristic) wind speed and the turbulent dispersion coefficients as functions of the height above the ground,[10] accounting for transient emission sources,[11] and including surface roughness.[12] Data also show that turbulence over urban areas is enhanced by 40% due to increased surface roughness and higher heat capacity.[9,13] Nevertheless, estimation of the dispersion coefficients by standard P-G curves seems sufficiently accurate for illustrating the effect of release conditions on the ITF and PITF. To facilitate numerical calculations in the present work, we used power law expressions of the form $\sigma = ax^{b + c\ln x}$, where a, b, and c are empirical parameters that vary with coordinate direction (y or z) and stability class.[14]

Substituting eq 10 into eq 2, the ITF for steady release from a point source can be expressed as

$$\text{ITF} = \frac{Q_B}{\pi\sigma_y\sigma_z U}\exp\left(-\frac{y^2}{2\sigma_y^{\ 2}}\right)\exp\left(-\frac{H_E^{\ 2}}{2\sigma_z^{\ 2}}\right) \qquad (11)$$

A similar equation for calculating the PITF, assuming a uniformly distributed exposed population, is derived from eqs 7 and 10

$$\text{PITF} = PQ_B\iint\frac{1}{\pi\sigma_y\sigma_z U}\exp\left(-\frac{y^2}{2\sigma_y^{\ 2}}\right)\exp\left(-\frac{H_E^{\ 2}}{2\sigma_z^{\ 2}}\right)dxdy \qquad (12)$$

This integral must be evaluated numerically. Bounds on the x coordinates extend from the source to the downwind edge of the populated area. Integration in the y direction can proceed outward from the plume center line until either the concentration diminishes to a negligible value or the outer edge of the populated area is reached.

The standard Gaussian plume model can be applied only for distances greater than 100 m from the source. For elevated releases with an effective stack height on the order of 30 m or so, this limitation does not pose a problem in evaluating the PITF. The ground-level concentration within the first 100 m downwind of the source is sufficiently small to make a negligible contribution to the PITF.

Line Source Emissions. Sometimes pollutants are emitted in a manner that can accurately be represented as a line source. A heavily traveled freeway is a common example. The rate of pollutant emission per unit length of the line source can be defined as E_{line} (g/m/hr). For a line source of length W, emitting at the ground ($H_E = 0$), with the wind direction perpendicular to the line source, the mass emission rate from any small interval of line source is given by $E_{line}\,dy$, where dy is the interval length. The concentration at the receptor contributed by the line source can be estimated by substituting $E_{line}\,dy$ for E in eq 10, and integrating over the length W. For example, if the receptor is at $y = 0$, the concentration can be expressed as

$$C(x) = \int_{-W/2}^{W/2}\frac{E_{line}}{\pi\sigma_y\sigma_z U}\exp\left(-\frac{y^2}{2\sigma_y^{\ 2}}\right)dy \qquad (13)$$

For a receptor at coordinate position x, Y ($Y > 0$) and for a source extending from $y = -W/2$ to $W/2$, the ITF can be expressed as

$$\text{ITF} = \frac{Q_B}{W}\int_{-Y-W/2}^{W/2-Y}\frac{1}{\pi\sigma_y\sigma_z U}\exp\left(-\frac{y^2}{2\sigma_y^{\ 2}}\right)dy \qquad (14)$$

For a line source of length W located along the upwind edge of a populated area of dimensions $W \times L$, the PITF over the entire air basin can then be determined by the following expression:

$$\text{PITF} = \frac{2PQ_B}{W}\left[\int_0^L\int_0^W\left(\int_{-Y-W/2}^{W/2-Y}\frac{1}{\pi\sigma_y\sigma_z U}\exp\left(-\frac{y^2}{2\sigma_y^{\ 2}}\right)dy\right)dYdx\right] \qquad (15)$$

As before, we have assumed a uniform population density and breathing rate throughout the air basin. The standard P-G dispersion coefficient curves are only valid for $x > 100$ m. For ground-level emissions, significant exposure may occur close to the source. To estimate the contribution to PITF for $x < 100$ m, we extrapolated the concentration profiles from 100 m to within 1 m of the source, using Davidson's power-law representations.[14] The ratios of the concentrations at 1–100 m were found to be within the range of 5–10, which agrees well with the available literature results.[15,16] With this in mind, the extrapolated profiles were integrated from distances 1m to 100 m, and the average concentration over the domain was evaluated. The population transfer factors were calculated according to eq 15. Due to the low total population for the first 100 m as compared with the whole modeling domain, it was found that the error for not considering the first 100 m would be less than 1% for all the cases studied.

Indoor Sources

Recent concerns related to environmental tobacco smoke, sick-building syndrome, and respiratory allergies, among other problems, have focused public and professional attention on indoor air quality. The ITF is well suited for exploring the significance of indoor emissions on inhalation dose. A simple model for estimating contaminant concentrations in the indoor environment considers the entire building as a single, well-mixed chamber. Exposures within more complex indoor environments can be evaluated using a model that incorporates mixing and transport between rooms or zones. Here, we will consider both conservative and depositing species for a well-mixed building (residence or office building) and for a six-zone, single-story residence.

Single Compartment. The concentration C (g/m^3) in a single zone is evaluated using a mass-balance equation and assuming well-mixed conditions. We have used two different approaches in considering pollutant losses within the system. The first approach ignores removal mechanisms other than ventilation, which is appropriate for cases in which they have a small impact on the overall concentration. The second approach includes an explicit, first-order loss term in the governing mass-balance equation. For the first approach, the solution to the mass conservation equation for a pollutant emission of short duration is

$$C(t) = \frac{M}{V}\exp\left(-\frac{Q}{V}t\right) \tag{16}$$

where t is the time since emission occurred (hr), M is the total contaminant mass emitted (g), V is the volume of the interior zone (m^3), and Q is the ventilation rate (m^3/hr).

For continuous emissions, the steady-state concentration is

$$C = \frac{m}{Q} \tag{17}$$

where m is the mass emission rate (g/hr). With the aid of eqs 1 and 2, the ITF can be evaluated. For both episodic and continuous emissions, the ITF is found to be

$$\mathrm{ITF} = \frac{Q_B}{Q} \tag{18}$$

For nonconservative pollutants, such as depositing particles and reactive gases, an additional loss term should be included. In this case, the ITF becomes

$$\mathrm{ITF} = \frac{Q_B}{(Q + \beta V)} \tag{19}$$

where β is the first order loss-rate coefficient (hr^{-1}) for processes other than ventilation. The loss rate for particles is size dependent and the loss rate for gases depends on the species reactivity, for example, with indoor surface materials. In calculations presented here, we estimate the loss rate coefficient for particles using a model that accounts for both sedimentation and diffusive deposition.[17]

The corresponding PITFs would be obtained by replacing Q_B in the numerator of eqs 18 and 19 with $\sum Q_B$ where the summation is carried out over all occupants.

Multicompartment Residence. Under some circumstances, pollutant concentrations within a multiroom residence cannot be predicted accurately using a single, well-mixed chamber model. If a pollutant is generated in one room, occupants in other rooms will also be exposed to that pollutant, but usually at lower levels than in the generation room. The magnitude of the difference depends on the airflow rates between the rooms, removal rates within rooms, and the air-exchange rate with the outdoor environment.

To illustrate the determination of ITFs for a multizone building, the general indoor air quality model, MIAQ4,[18] was used to model the species concentrations within a six-zone residence. MIAQ4 tracks the evolution of the chemical composition and aerosol size distribution as it is affected by inter-room mixing, ventilation, filtration, emission, coagulation, and deposition onto indoor surfaces. An important feature of this model is the ability to account for generation and loss rates, which vary according to particle size. The infiltration, exfiltration, and interzone flow rates are model inputs that can be obtained from experimental data or from interzone flow models.[19]

Single Compartment Vehicle. For estimating transfer factors from emissions into the small air volume within a motor vehicle, it is reasonable to model the interior as a single, well-mixed compartment. Furthermore, the high air-exchange rates within a vehicle reduce the importance of loss mechanisms, such as surface reaction and deposition. Therefore, the equations developed for a conservative pollutant in a single, well-mixed chamber (eqs 16–18) provide a good estimate of conditions within a vehicle. In this paper, ITFs for pollutants generated within the passenger compartment will be presented for six conditions, using data on the effects of vehicle motion, window position, and fan operation on ventilation rate.

RESULTS

With the equations developed in the previous section, we can evaluate ITFs for releases in both outdoor and indoor environments. For outdoor release scenarios, we assume that the receptor of interest is also outdoors. For conservative pollutants, the time-integrated inhalation exposure for indoor receptors is similar to that outdoors. For indoor releases, we will consider only exposures to people within the building where the pollutant is released. Exposures to individuals downwind of the source building are generally much smaller, both in terms of individual and cumulative population exposure, and so are not included here.

Uniformly Mixed Pollutant Outdoors

When using the well-mixed air basin model, the individual ITF depends on the crosswind dimension of the air basin, the mixing height, and wind speed. We modeled populated areas ranging in size from 10 × 10 km to 100 × 100 km and wind speeds between 1 (calm) and 10 m/sec (moderately windy). For all cases, we chose a mixing height of 300 m and a breathing rate of 0.78 m^3/hr.[20] We examined the PITFs for population densities ranging from 1000 (typical suburban) to 6000 km^{-2} (typical urban).[21] Table 1 shows the ITFs and PITFs for three populated areas, three wind speeds, and two population densities.

Over the ranges of variables studied, the ITF varies by a factor of 10 for changes in either wind speed or size of populated area. Higher wind speeds and larger populated areas both decrease the ITF. When assessing the overall significance of the emission of a toxic air pollutant, the exposure to the entire population is often of concern. Therefore, it is also important to consider differences in PITF values for the various conditions. As in the case of ITFs, the PITF is inversely proportional to wind speed. However, the PITF is proportional to the windward dimension of the populated area and to population density.

The magnitude of the ITF for this set of cases is in the range of ~10^{-12}–10^{-10}, meaning, for example, that an inhabitant of a well-mixed urban zone would inhale 0.7–70 ng of a contaminant per kg emitted. Collectively, all inhabitants of a densely populated area (P = 6000 km^{-2}) would inhale 4–400 mg/kg emitted.

Table 1. ITFs and PITFs for outdoor emissions into a well-mixed air basin.[a]

Size of Populated Area (length km × width km)	Wind Speed (m/sec)	ITF ($\times 10^{-12}$)	PITF ($\times 10^{-6}$)[b,c] (P = 1000 km^{-2})	PITF ($\times 10^{-6}$)[b,c] (P = 6000 km^{-2})
10 × 10	1	73	7.3	44
	4	18	1.8	11
	10	7.3	0.7	4.4
30 × 30	1	24	22	130
	4	6	5.4	32
	10	2.4	2.2	13
100 × 100	1	7.3	73	440
	4	1.8	18	110
	10	0.73	7.3	44

[a]Mixing height taken to be H = 300 m; [b]PITFs computed assuming uniform population density throughout the air basin; [c]Breathing rate of 0.78 m^3/hr assumed.

Point Source Emissions

For point source emissions, the shape of the plume and the concentration within it depend on atmospheric stability, wind speed, and height of the emission source. We considered wind speeds of 1, 4, and 10 m/sec and a breathing rate of 0.78 m^3/hr. We looked at source heights of 30 and 100 m and three stability classes: B (unstable), D (neutral), and E (slightly stable). Figure 1 shows ground-level ITF isopleths for selected meteorologic conditions and a stack height of 30 m.

PITFs for different population densities can be found by numerically integrating the ITF values over the populated area. The results for a range of population densities and meteorological conditions are shown in Table 2. Note that the magnitudes are similar to those presented in Table 1 for the well-mixed basin. For a tall stack upwind of a small population center, the PITF for neutral conditions (D) is higher than for slightly stable conditions (E). Under stable conditions, the plume does not reach ground level for a considerable distance downwind, and a large portion of the populated area does not have a significant exposure. With this exception, the basic trends in PITF values follow those of ITF values.

For the range of conditions considered, the maximum PITF (190 × 10^{-6}) occurred for a 30-m-high release in a large populated area under the most stable conditions (E) at a moderate wind speed (4 m/sec). The minimum PITF (0.8 × 10^{-6}) occurred for a tall stack (100 m) in a small, moderately populated area under neutral conditions (D) with the highest wind speed (10 m/sec). At this minimum value, 0.8 mg of pollutant for each kg released would be inhaled by an individual within the populated area. These results are indicative of the range expected for pollutant release from an elevated point source upwind of a populated area.

Line Source Emissions

For line source emissions, the pollutant source is assumed to be perpendicular to the wind, positioned along the upwind edge of a populated area, and of the same width as the populated zone. As we did for the point source, we investigated wind speeds of 1, 4, and 10 m/sec, a breathing rate of 0.78 m^3/hr, and stability classes B, D, and E. The emission height is set to 0 to simulate a ground-level source, such as vehicle exhaust from a highway. Figure 2 shows the ITF as a function of distance from the source for selected conditions.

Using eq 15, the PITF can be evaluated by integrating the curves in Figure 2 and multiplying by the population density. Table 3 shows the PITFs for high and moderate population densities downwind of a line source at y = 0. The PITF values for a line source are similar in magnitude to those for a point source and for the well-mixed air basin.

Well-Mixed Indoor Environment

For a conserved species released within a single, well-mixed compartment, the ITF is inversely proportional to the outdoor air ventilation rate. In residential buildings, ventilation is typically expressed in terms of an air-exchange rate, Q/V. We looked at a range of air-exchange rates from 0.2 (representing a well-sealed building of modern construction)

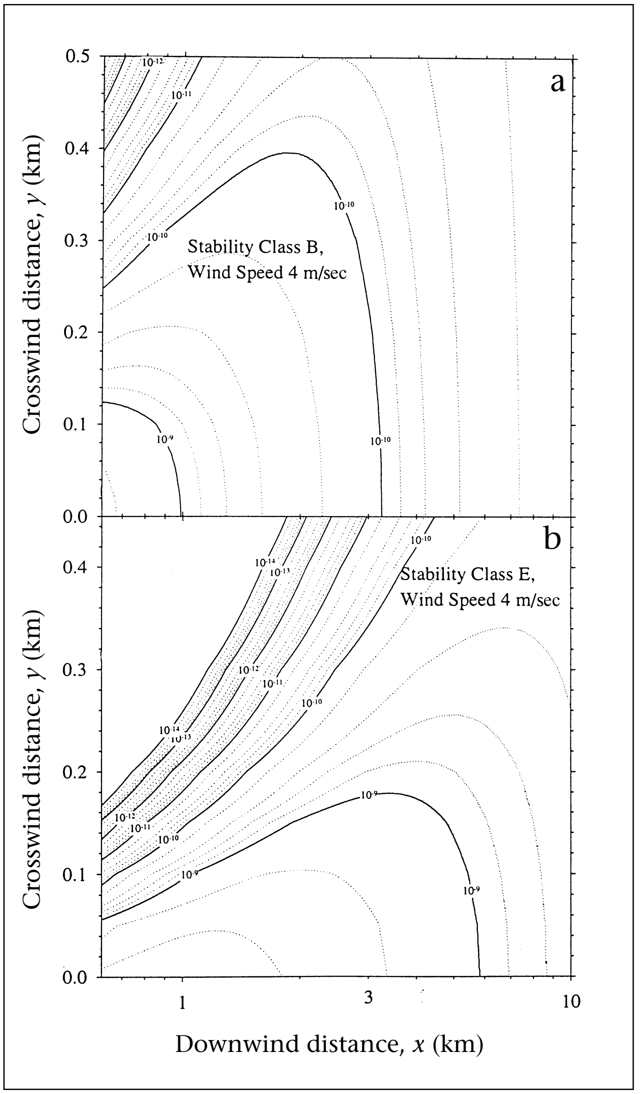

Figure 1. ITF isopleths for an outdoor point source at a 30-m height as predicted using a Gaussian plume model: (a) wind speed 4 m/sec and stability class B (unstable) and (b) wind speed 4 m/sec and stability class E (slightly stable). Note logarithmic scale for downwind distance, *x*. Dotted lines represent 2, 4, 6, and 8 times the lower value of the adjacent labeled isopleth.

to 2 hr^{-1} (representing an older, drafty building) for a typical single-family residence (V = 350 m^3).[22,23] As before, we assumed an average breathing rate of 0.78 m^3/hr. For a conservative pollutant (eq 18), the ITFs ranged from 0.01 for a tight building to 0.001 for a drafty building. Assuming three occupants in the residence, the corresponding PITF values are 0.03 and 0.003, respectively. Once the conserved pollutant is removed by ventilation, exposures can occur to persons downwind of the building. These exposures would be analogous to those resulting from outdoor emission from a ground-level point source. Because transport and mixing is more rapid outdoors than indoors (especially vertically), the contribution to PITF is much smaller for outdoor exposures than for indoor exposures from indoor releases.

As an example of a nonconserved pollutant, we determined the ITF for particles of different sizes. Using results from a study of the loss rate coefficient β, and assuming a typical turbulence intensity,[17] the ITF was calculated for ventilation rates between 0.2 (tight) and 2 (leaky) hr^{-1}. The ITF ranged from 0.0002 for 10-μm particles at a high air-exchange rate to 0.01 for ~0.15-μm particles at a low air-exchange rate (see Figure 3).

Similar calculations were made for a five-story, prototypical office building, with a total floor area of 22,000 m^2, an occupied volume of 59,400 m^3, and 1540 occupants (based on seven people per 100 m^2).[24] For an outdoor fresh air intake rate of 10 L/sec/person (= 55,400 m^3/hr) and Q_B = 0.78 m^3/hr, the ITF and PITF for conserved species are 1.4×10^{-5} and 0.02, respectively. The PITF is similar to the value found for three occupants in a low ventilation-rate house.

Multichamber Residence

We examined the case of a six-zone, single-floor residence with an overall air-exchange rate of ~0.8 hr^{-1}. Detailed dimensions and airflow rates are shown in Figure 4.[25] For the simulation, we assume that the pollutants of concern are emitted indoors, each compartment is independently well-mixed, and the breathing rate is 0.78 m^3/hr. Two different flow scenarios and two source locations were simulated. In one scenario, all interiors doors are open. In the other scenario, the bathroom door is closed, the bathroom fan is on, and all other interior doors are open. The source is either in the living room or in the bathroom. Figure 5 shows ITFs for each zone for a conserved species. When the source is in the living-room, the high interzonal flow rates and the large living-room volume cause the variations among ITFs in different zones to be modest. With the source in the living room and the fan on in the bathroom, the concentration in the bathroom is relatively low and the fan is not effective at reducing exposures within the residence. When the source is in the bathroom, the small room volume causes a high initial concentration in the bathroom and, hence, a high local ITF. With the fan turned off, ITFs for the bedroom, kitchen, and hallway are essentially the same for either a bathroom or living-room release. As expected, turning on the bathroom fan and closing the bathroom door is highly effective at removing pollutants from a bathroom source and reduces the ITFs at all locations.

For a nonconservative pollutant, the ITF depends on the loss rate, for example, by deposition or reaction on indoor surfaces. From the results shown in Figure 3, the ITFs for particle diameters of 0.1-μm magnitude are expected to be very close to the results shown in Figure 5. However, for particles much larger or smaller than ~0.1 μm, or for reactive gases, deposition will reduce the ITFs.

Table 2. PITFs for an elevated point source upwind of a populated area.

Plume Extent[a] (length km × width km)	Wind Speed (m/sec)	Stack Height (m)	Stability[b]	PITF (×10^{-6})[c] (P = 1000 km^{-2})	PITF (×10^{-6})[c] (P = 6000 km^{-2})
10 × 20	1	30	B	5.3	32
	1	100	B	3.6	22
	4	30	B	1.3	8.0
	4	30	D	4.8	29
	4	30	E	6.3	38
	4	100	B	0.9	5.4
	4	100	D	2.0	12
	4	100	E	1.3	8.0
	10	30	D	2.0	12
	10	100	D	0.8	4.8
100 × 20	4	30	D	17	100
	4	30	E	31	190
	4	100	D	14	84
	4	100	E	22	130
	10	30	D	6.8	41
	10	100	D	5.6	34

[a]Assumes uniform population density extending over the dimensions indicated; [b]Stability classes: B (unstable), D (neutral), and E (slightly stable); [c]Breathing rate of 0.78 m^3/hr assumed.

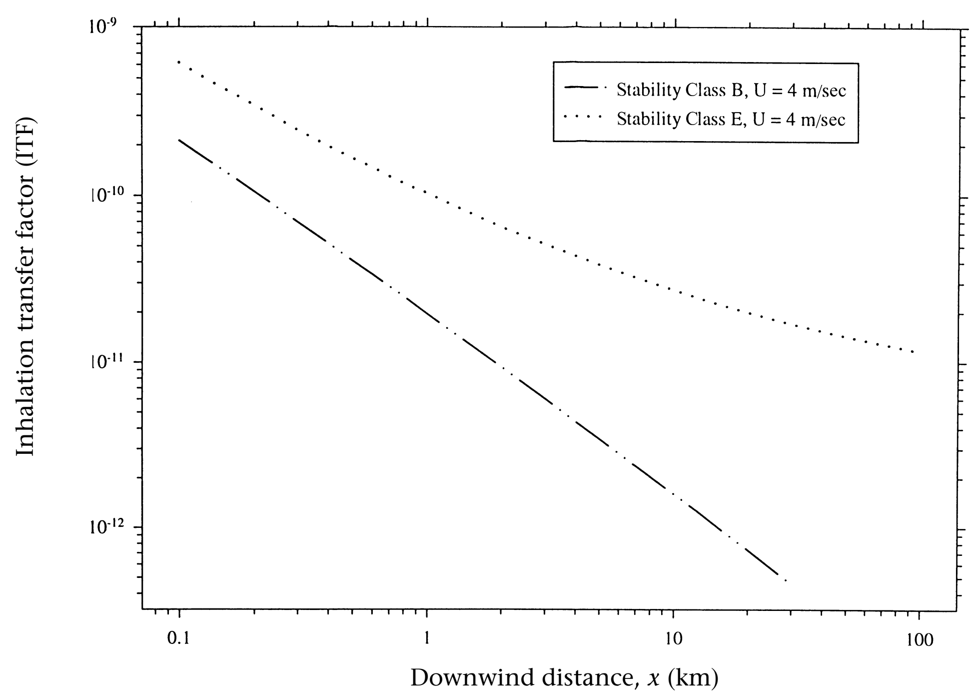

Figure 2. ITFs as a function of downwind distance for a ground-level line source at y = 0, for stability classes B (unstable) and E (slightly stable) and wind speeds of 4 m/sec. The length of the line source is equal to the width of the air basin, which extends from y = –10 to 10 km.

Table 3. PITFs for a ground-level line source upwind of a populated area.

Size of Populated Area[a] (length km × width km)	Wind Speed (m/sec)	Stability[b]	PITF ($\times10^{-6}$)[c] ($P = 1000$ km^{-2})	PITF ($\times10^{-6}$)[c] ($P = 6000$ km^{-2})
10 × 20	1	B	15	90
	4	B	3.7	22
	4	D	15	90
	4	E	22	130
	10	D	5.9	35
30 × 20	1	B	17	100
	4	B	4.3	26
	4	D	24	140
	4	E	39	230
	10	D	9.5	57

[a]Size of populated area directly downwind of line source, which is oriented perpendicular to the wind. Line source dimension is the width of populated area; [b]Stability classes: B (unstable), D (neutral), and E (slightly stable); [c]Uniform population density downwind of source; breathing rate of 0.78 m^3/hr assumed.

Motor Vehicles

We assumed an interior volume of 3 m^3 and based the estimates of air-exchange rates on reported results for a stationary vehicle and for a moving vehicle.[26,27] All pollutants in the vehicle were treated as conservative. The air-exchange rates and corresponding ITFs for emissions within a vehicle are shown in Table 4. The ITFs range from 0.3 for a stationary vehicle with no forced ventilation to 0.002 for a moving vehicle with the windows open. Because of the small volume of a vehicle, ITF values can be significantly higher than the transfer factors within buildings when the vehicle is stationary with its windows closed. The ITFs in a moving vehicle are similar to those in residences.

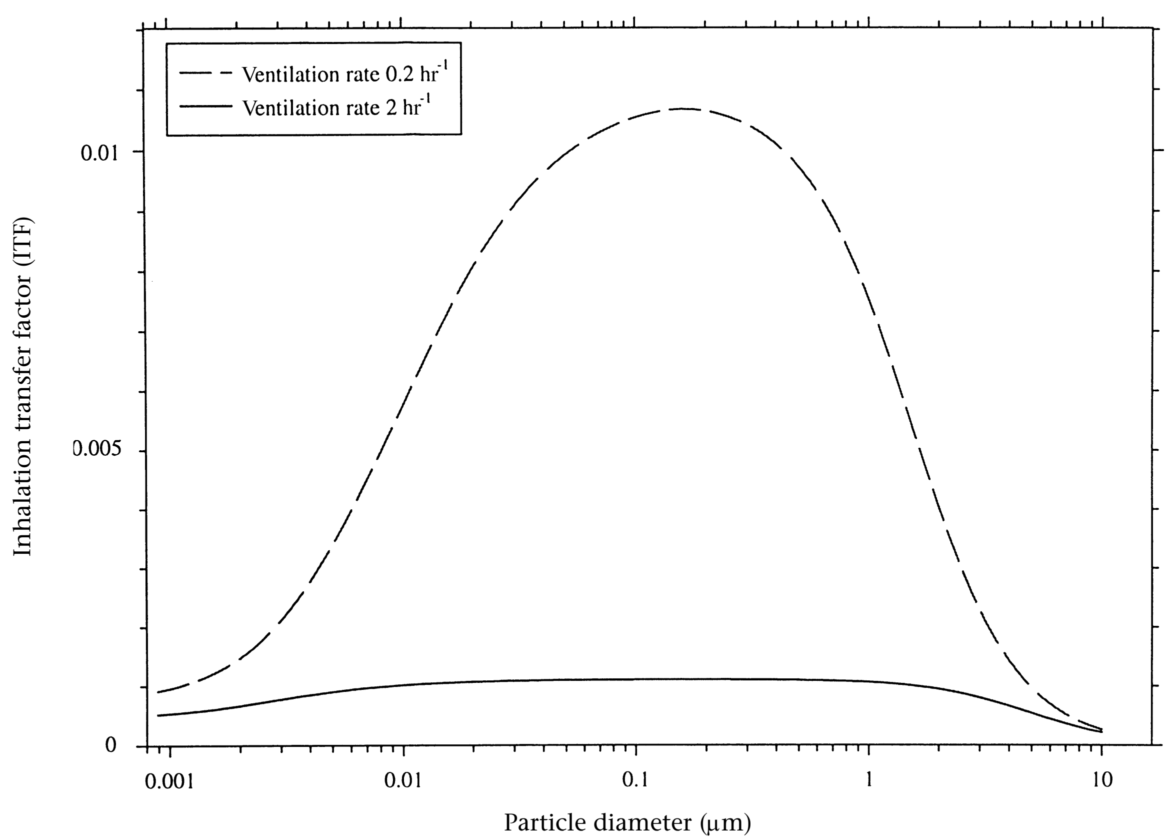

Figure 3. ITF as a function of particle size for a release in a single, well-mixed building, with volume 350 m^3, for two air-exchange rates. Calculations assume surface-to-volume ratio of 3 m^{-1} with 50% of surfaces vertically oriented, and 25% upward and 25% downward horizontally. The friction velocity is assumed to be 1 cm/sec. Particle density is 1 g/cm^3.

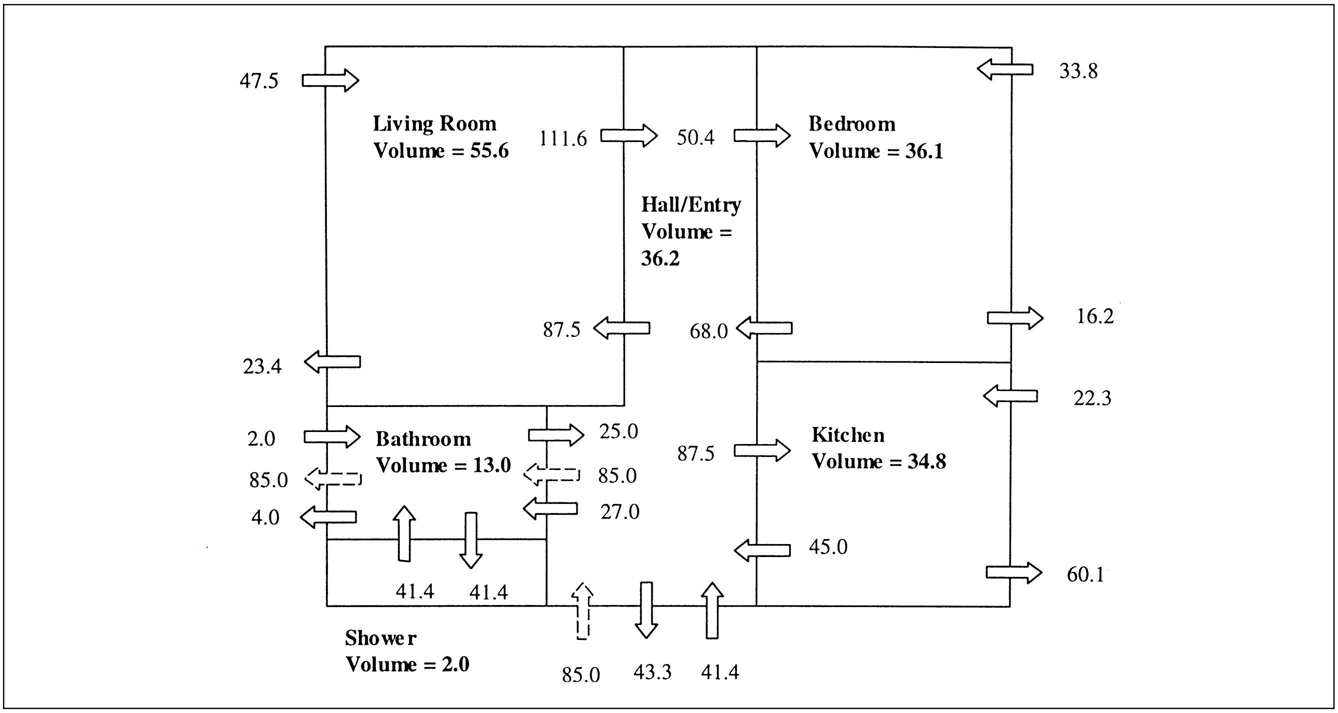

Figure 4. Dimensions and interzonal flows within a six-zone, single-floor house. Volumes are in m^3 and airflow rates are in m^3/hr. In the baseline case, all interior doors are open. In the second case, the bathroom door is closed and the bathroom exhaust fan is operating. The additional effect of the fan is shown with broken arrows.

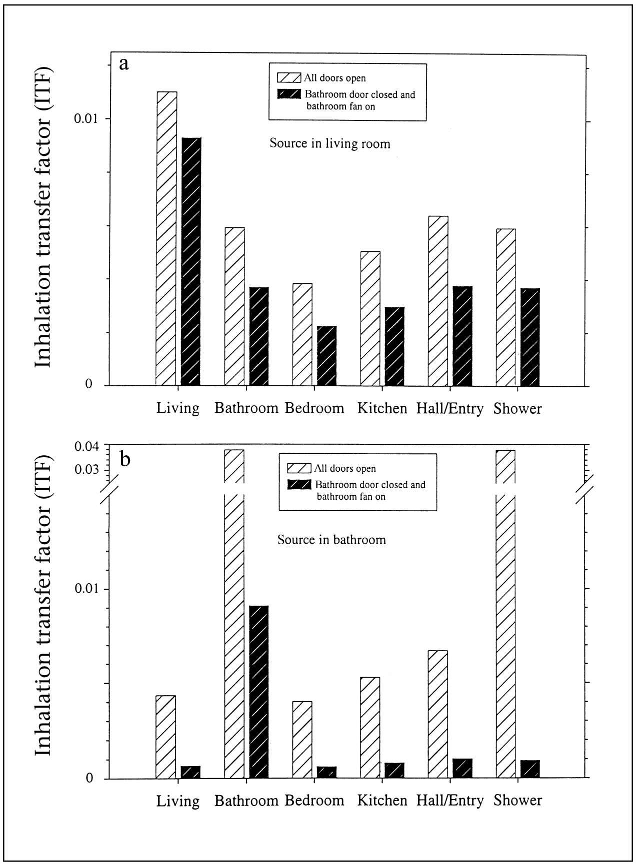

Figure 5. ITFs for a release within a six-zone residence for two different flow regimes and with two different release locations: (a) source in living room and (b) source in bathroom.

SUMMARY

Figure 6 presents a summary of PITF results obtained for the cases considered in this paper. Outdoor emissions into moderately or densely populated areas lead to PITF values that are generally in the range of 10^{-6}–10^{-3}. Indoor emissions in residences or office buildings produce PITF values of 10^{-3}–10^{-1}. Emissions in moving vehicles produce a similar range of results as in buildings.

CONCLUSIONS

Pollutant emissions of the same magnitude do not necessarily lead to the same level of exposure and hazard. In developing a quantitative scheme for determining health risk, Zartarian et al. observed that one of the key exposure assessment issues is determining the effectiveness of delivery "from the source to the target."[5] Typically, assessing potential exposures to air pollutant emissions involves detailed transport and dispersion modeling with substantial data requirements. However, a simpler process that requires much less effort can be used to obtain estimates. To this end, we have defined and proposed the use of ITFs. These are analogous in concept and potential applicability to the widely used emission factors for assessing pollutant emissions.

The ITF has been shown to be an effective measure for comparing the magnitude of individual exposures to pollutant emissions released under different conditions. An additional measure, the PITF, was introduced to describe the total amount of an emitted pollutant inhaled by all members in the exposed population. To demonstrate the usefulness of these concepts, ITF and PITF values were calculated for several release scenarios.

For the exposure scenarios studied, ITFs ranged enormously, from 10^{-12} to 10^{-1}. The most significant variable influencing the magnitude of the ITF was whether the emission occurred indoors (or in a vehicle) or outdoors. Individual ITFs for indoor emissions were many orders of magnitude higher than for outdoor emissions. Even when inhalation by the total exposed population was calculated, PITFs were typically a few orders of magnitude higher for indoor or in-vehicle emissions than for outdoor emissions. Although the total number of exposed individuals is much higher outdoors, the effects of increased dispersion and more effective wind clearance (as compared with building ventilation) reduce the total fraction of the pollutant inhaled.

In the room with the source, transfer factors for indoor emissions were not highly sensitive to the model used. ITFs calculated using the more complex MIAQ4 model were close to those from a simple well-mixed model. For emissions within a vehicle, the small interior volume produces the highest ITF values for cars when the vehicle is stationary and the windows are closed. When the vehicle is moving, high rates of ventilation combine with the small volume to provide ITFs that are similar to those estimated for residences.

Further development of ITFs could lead to more efficient and transparent health risk assessments for air pollutant emissions. For example, if the ITF and PITF concept were to become widely accepted, an ITF handbook could

Table 4. ITFs for an occupant within a vehicle with an internal pollutant source.

Scenarios	Fan Setting	Window Condition	Air-Exchange Rate (ACH)	ITF[a]
Stationary vehicle, wind speed 1 m/sec	Off	Closed	1	0.3
Stationary vehicle, wind speed 10 m/sec	Off	Closed	8	0.03
Stationary vehicle, wind speed 1 m/sec	On	Closed	1	0.3
Stationary vehicle, wind speed 10 m/sec	On	Closed	10	0.03
22 km/hr, wind speed < 4 m/sec	Off	Closed	14	0.02
44 km/hr, wind speed < 4 m/sec	Off	Closed	40	0.007
32 km/hr	NA[b]	Open	120	0.002

[a]Assumes Q_B = 0.78 m^3/hr; [b]Data not available.

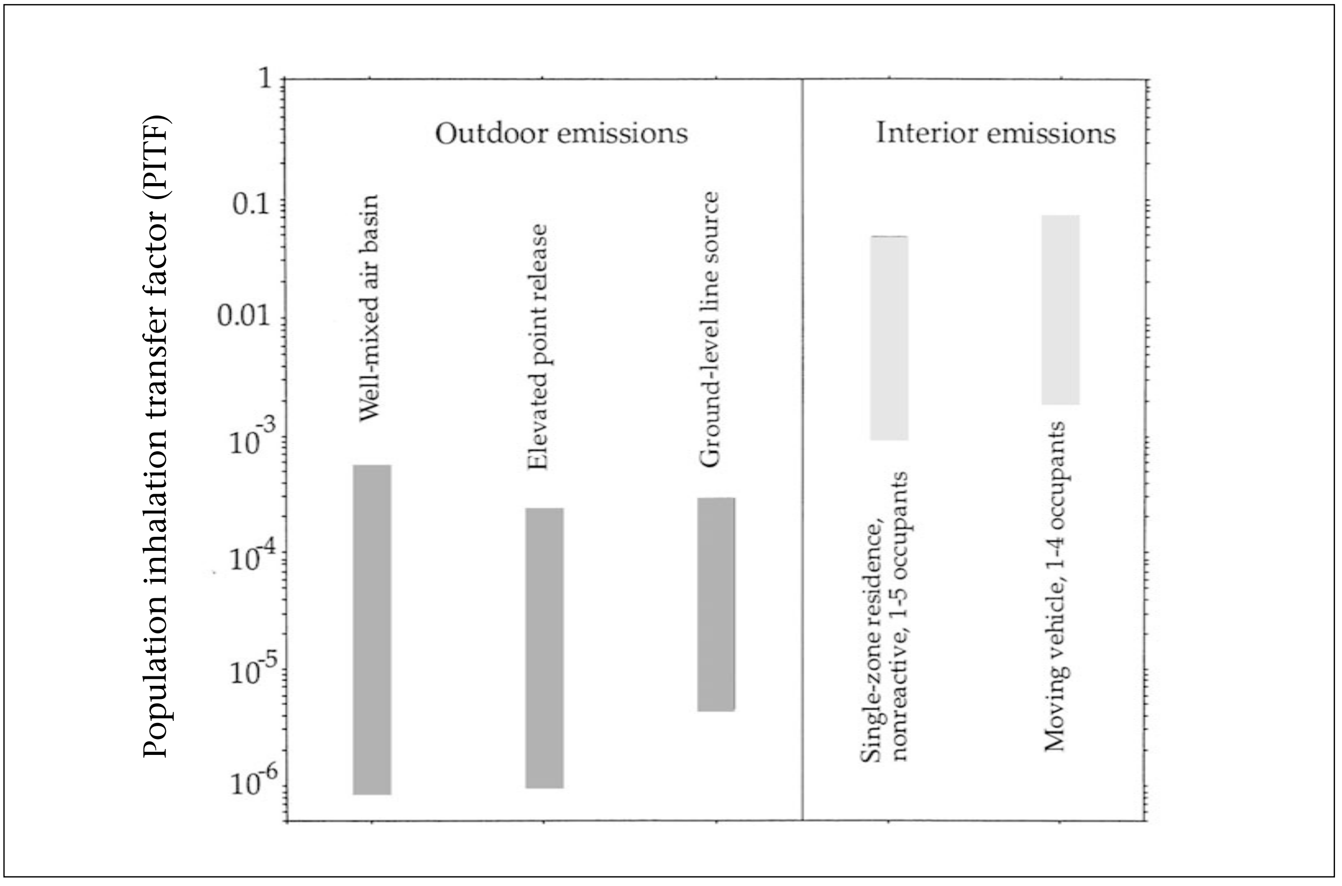

Figure 6. Summary of PITFs for release conditions considered in this paper.

be compiled. This handbook would be analogous to the emission factors handbook (AP-42) maintained by the U.S. Environmental Protection Agency.[28] The ITF handbook would allow an analyst to connect emissions to inhaled dose without the need to run data-intensive Gaussian plume simulations. To develop such a handbook, the calculation approaches discussed in this paper would need to be refined, for example, to better account for near-source contributions to exposure. Calculations would also be needed over a much wider range of conditions.

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